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COLD WELDING IN A VACUUM: AN ANNOTATED BIBLIOGRAPHY

SPECIAL BIBLIOGRAPHY
SB-63-5

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NOTICE

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Compiled by
SCOTT J. BUGINAS

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Lockheed

MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA

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ABSTRACT

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INTRODUCTION

Basic work in this field dates back to that performed by F. P. Bowden, T. P. Hughes, D. Tabor and J. E. Young reported in the ROYAL SOCIETY PROCEEDINGS beginning in the late thirties. Bibliographies by Abbott (1)*, Hansen (16)*, and Owens (30)* will provide the user with additional and related information.

Very few recent experiments have been reported in the vacuum range 10^{-9} Torr and higher. Much of the reported work has been oriented around the aspects of friction, seizing and lubrication rather than cold welding.

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*Numbers refer to references cited in this bibliography.

TABLE OF CONTENTS

1. Abbott, H. M., Comp.
SPACE ENVIRONMENTAL EFFECTS ON GEARS AND BEARINGS: AN ANNOTATED BIBLIOGRAPHY.
Lockheed Missiles and Space Division, Sunnyvale, Calif. Special Bibliography No. SB-61-49, Oct 1961.
72p. ASTIA AD 269556

An annotated bibliography on gears and bearings, resulting from a general literature search as an aid to the consideration of design factors, temperature, speed effects and wear problems on materials that could give satisfactory service in spacecraft applications.

2. Atkins, J. H., et al.
EFFECTS OF SPACE ENVIRONMENT ON MATERIALS
Wright Air Development Division, WPAFB, Ohio.
Technical Report no. WADD TR 60-721, Dec 1960.
66p.

Discusses the effects of radiation and high vacuum on materials. Reviews tests and work being done and proposed at 10^{-9} mm Hg and lower.

3. Brueschke, E. E. and R. H. Suess
SEIZURE OF METALLIC SURFACES IN ULTRAHIGH VACUUM. Hughes Aircraft Co., Culver City, Calif. Technical Memorandum No. TM-685. 15 Jul 1961. 16p. NASA N62-13637

An experimental study has been made of the seizure of thoroughly degassed metallic surfaces in ultrahigh vacuum. Information compiled from the laboratory investigations and from the literature is presented in this document as an aid to understanding metallic seizure in vacuum. The conditions under which seizure of such surfaces will occur are discussed, and methods of preventing seizure are presented. (Author)

4. Buckley, D. H. and R. L. Johnson
EFFECT OF INERT, REDUCING AND OXIDIZING ATMOSPHERES ON FRICTION AND WEAR OF METALS TO 1000°F. Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio. Report no. NASA TN D-1103, Oct 1961. 26p. (Also digested in METAL PROGRESS 82:144,150, Jul 1962)

The absence of oxides on metal surfaces resulted in excessive wear and high friction of metals. In certain instances where surfaces were devoid of oxides mass welding of the specimens occurred. When extremely small quantities of oxygen were present, in the atmosphere, oxides formed on the metal surface to form adequate protection.

5. Buckley, D. H., M. Swikert and R. L. Johnson
Friction, wear, and evaporation rates of various materials in vacuum to 10^{-7} mm Hg. AMERICAN SOCIETY OF LUBRICATION ENGINEERS. TRANSACTIONS 5:8–23, Apr 1962. NASA N62-13625

Evaporation data on soft metals, lubricating inorganic compounds, and various reference materials are reported for temperatures from 75° to 1000°F in vacuum as low as 10^{-7} mm Hg. Observations on modes of vacuum degradation (e.g., evaporation or dissociation) and methods of experimentation are related. Friction and wear data are presented for several unlubricated metals (e.g., type 440-C steel) and metals coated with inorganic (e.g., MoS_2, CaF_2), as well as with soft metal films in vacuum at ambient pressures between 10^{-6} and 10^{-7} mm Hg. (Author)

6. Clauss, F. J., et al
Evaluating the behavior of materials under space conditions. In INSTITUTE OF THE ENVIRONMENTAL SCIENCES, PROCEEDINGS. Mt. Prospect, Illinois, The Institute, 1961. p.475–488.

Describes some of the research studies at Lockheed and presents some of the data concerning the problems of materials in space. Areas discussed are; wear and seizure of rubbing surfaces under high vacuum, temperature control surfaces, stability of organic adhesives. Some information is given on the operation of bearings in a high vacuum.

7. Clauss, F. J., et al
Sliding contacts and friction phenomena in space.
In ADVANCE PAPERS OF THE ASM 1962 GOLDEN GATE METALS CONFERENCE ON MATERIALS SCIENCE AND TECHNOLOGY FOR ADVANCED APPLICATION, San Francisco, Calif.
15–17 Feb 1962. p.141–165.

When absorbed or chemisorbed gas films which are present on metallic surfaces in our atmosphere are removed by wear or sublimation in the hard vacuum of outer spacc, cold welding can occur. Adequate lubrication must be provided.

8. "Cold-welding" in vacuum holds risks and promise.
SPACE AERONAUTICS 37:47, May 1962.

Strong homogenous joints are formed in copper by surface diffusion at -200°C in vacuum.

9. Colner, W. H.
Space-new environment for materials.
MATERIALS RESEARCH & STANDARDS
2(8):656–660, Aug 1962

Information on a laboratory vacuum system capable of achieving a vacuum of 10^{-7} mm Hg.

10. Convair, San Diego, Cal.
INTERCEPTOR SUBSYSTEM RESEARCH FOR BALLISTIC MISSILE DEFENSE. VOLUME III. HIGH-VACUUM FRICTION PHENOMENA.
Final report no. ZR-AP-030, Jul 1960. 34p.
(WADD TR 60-400, vol. 3) ASTIA AD-253 659

Evidence was presented that the friction of metal surfaces under low loads in air may not be due largely to the mechanism described by the adhesion theory of friction. Calculations indicate that if the adhesion theory were responsible for the observed friction of metals, then adhesion should be easily measurable, in spite of the effect of released elastic stresses. It was found that for copper and evaporated copper on metal substrates, adhesion (in the absence of sliding) could only be measured when the specimens were free from contamination by air. It is concluded that it is not the effect of relieved stresses but the presence of a contaminant film, probably oxide, which prevents detection of adhesion for copper in the absence of sliding. Other experiments were performed with copper and gold to determine if there exists the correlation between friction and adhesive forces presumed by the adhesion theory While there is a definite correlation in air at large coefficients of friction, there is none below a value of approximately one-half. A mechanism was proposed to account for friction in the absence of adhesion. (Author)

11. THE DANGEROUS VACUUM OF SPACE
Mechanical Engineering, 83(12):84, Dec 1961.

The effects of the vacuum of space on materials and lubricants are briefly considered.

12. Franklin, W.
ADHESION BETWEEN ATOMICALLY CLEAN METALLIC SURFACES. PART 2, DETERMINATION OF THE SURFACE ENERGY OF SILVER AT -187°C. Syracuse University Research Institute, N.Y. Report no. S.U.R.I. MET. E. 905-621SA, 1 Feb 1962. p.13–19. NASA N62-13821.

13. Freitag, E. H.
The friction of solids. CONTEMPORARY PHYSICS 2(3):198–216, Feb 1961.

The friction of metals, including adhesion theory, plastic and elastic deformation is described. Non-metals, friction at high speeds and at high temperatures are also discussed.

14. Hamm, John L.
INVESTIGATION OF ADHESION AND COHESION OF METALS IN ULTRAHIGH VACUUM.
First Quarterly Progress Report, 15 June to 15 September 1961. National Research Corp., Cambridge, Mass. 20 Sep 1961. 8p. (Contract NASr-48) NASA N62-10571.

Apparatus for the measurement of cohesion has been modified and calibrated in preparation for initial tests on O.F.H.C. copper by the fracture-rejoining method proposed.

15. Ham, J. L.
Mechanisms of surface removal from metals in space. AEROSPACE ENGINEERING. 20:20–21, 49–52, May 1961.

Discusses the oxidation rate in ultrahigh (10^{-10} mm Hg +) vacuum, loss of surface films, metal evaporation, dissociation and effects on metal properties.

16. Hansen, S., W. Jones, and A. Stephenson
RESEARCH PROGRAM ON HIGH VACUUM FRICTION. Litton Industries, Space Research Laboratories, Beverly Hills, Calif. Final Report 2907, 30 Mar 1959. 148p. (AFOSR TR-59-97) ASTIA AD-227,352.

The authors examined the friction characteristics of a large group of materials under conditions of high vacuum (10^{-5} to 10^{-6} mm Hg). The principal test condition studied was that of the linear motion between two dry, clean, unlubricated, flat surfaces. A bibliography of 71 items is appended.

17. Heilingbrunner, O.
Friction phenomena in vacuum. VAKUUM-TECHNIK 4:133–139, Jan 1956. (In German)

An experimental arrangement and procedure is described which permits assessment of the proportion of elastic collisions between molecules and the wall of a vessel. The results of the measurements are discussed and their significance with regard to the mechanism of friction in a vacuum is investigated.

18. Hofmann, W. and H. J. Schueller
Improvements in cold pressure welding.
ZEITSCHRIFT FUER METALLKUNDE
49:302–311, Jun 1958. (In German)

Gold and silver are butt welded in a high vacuum. Oxide film effects, specimen configuration and deformation are discussed.

19. How metals react in space. STEEL
149:58–59, 2 Oct 1961.

20. Jaffee, L. D.
Space vacuum poses design problems.
NUCLEONICS. 19:93–94, Apr 1961.

Information on evaporation, sublimation and friction reduction is presented. Testing in a vacuum is discussed.

21. Jaffee, L. D. and J. B. Rittenhouse
BEHAVIOR OF MATERIALS IN SPACE ENVIRONMENTS
California Institute of Technology, Jet Propulsion Lab., Pasadena, Calif. Technical Report No. 32-150, 1 Nov 1961. p.18–24.

Discusses friction and lubrication.

22. Jaffee, Leonard D. and John B. Rittenhouse
EVAPORATION EFFECTS ON MATERIALS IN SPACE. California Institute of Technology, Jet Propulsion Laboratory, Pasadena, Calif. Report no. JPL-TR-32-161, 30 Oct 1961. 20p. (NASA Contract NASw-6) NASA 62-12744.

Sublimation of inorganic materials in the vacuum of space can be predicted accurately from knowledge of their vapor pressures and, for compounds, of their free energies.

Among the elements, cadmium, zinc and selenium are readily lost near room temperature and magnesium at elevated temperatures. Selective loss at individual grains and at grain boundaries can produce some surface roughening. Engineering properties are, in general, little affected in vacuum unless appreciable loss of mass occurs. (Author)

23. Jaffee, L. D. and J. B. Rittenhouse
How materials behave in space. MATERIALS IN DESIGN ENGINEERING 56:97–104, Sep 1962.

Includes a discussion of wear and seizing of various materials.

24. Johnson, V. R., G. W. Vaughn, and M. T. Lavik
Apparatus for friction studies at high vacuum. REVIEW OF SCIENTIFIC INSTRUMENTS 27:611–613, Aug 1956.

Describes a friction test apparatus employing coupled magnets used for friction studies of dry lubricants under high vacuum.

25. Keller, Douglas V., Jr., and T. Spalvins
FRETTING AND DRY FRICTION UNDER SPACE CONDITIONS. Syracuse U. Research Inst., N.Y. Final Report. 30 Jun 1961. 58p. NASA N62-13820

26. Kerner, A.
ADHESION BETWEEN ATOMICALLY CLEAN METALLIC SURFACES. PART 3. DETERMINATION OF THE STRUCTURE OF THE INTERFACE FORMED IN ADHESION. Syracuse University Research Institute, N.Y. Report no. S.U.R.I. MET E. 905-621SA, 1 Feb 1962. p.20–24. NASA N62-15678

27. Kurzeka, W. J.
BEARING MATERIALS COMPATIBILITY FOR SPACE NUCLEAR AUXILIARY POWER SYSTEMS.
Atomics International Div. of North American Aviation, Inc., Canoga Park, Calif. Report no. NAA-SR-6476. 1 Sep 1961. 60p. (Contract AT-11-1-GEN-8).

A program to evaluate materials for suitability as exposed bearings on nuclear auxiliary power systems (SNAP Program) for space vehicles is reported. Friction coefficients of material combinations in a 10^{-6} mm Hg vacuum at 1000°F for 200 hr were measured. Seven combinations found to have friction coefficients less than 0.50 are: graphite-Haynes 90; graphite-Stellite No. 3; graphite-Al_2O_3 (sprayed); Al_2O_3 (sprayed)-Cr_3C_2 sprayed); Al_2O_3 (sprayed)-TiC; Al_2O_3 (solid)-3-F-12; and Al_2O_3 (solid)-3-N-12. (Author)

28. Ling, F. F.
WELDING ASPECT OF SLIDING FRICTION BETWEEN UNLUBRICATED SURFACES.
Rensselaer Polytechnic Institute, Troy, N.Y. Final Report, Jun 1960. 46p. (AFOSR TR-60-117) ASTIA AD-243 444.

On adhesion under partial vacuums and elevated temperatures: The logarithmic coefficient of adhesion, σ, vs. temperature was plotted for Au-Au and Cu-Cu systems. The load of 670 grams was applied in 1 hour. The environment was maintained at 760, 10^{-3}, and 10^{-6} mm Hg. For the short range of σ, the data were nearly in straight lines; the apparatus was designed to measure adhesion no larger than 4 times the normal load. As the pressure decreased, the slope increased, with the Cu-Cu system having a smaller slope than the Au-Au. At 10^{-6} mm Hg the Q'/R was 10^5 degrees K which is approximately comparable to the activation energies of self diffusion of Au and Cu. At the same pressure, the variation of σ with respect to loading time at 80°C was plotted with a load of 670 grams. The data indicate that σ was related to activation energy of the process and a time exponent, both of which are dependent on the degree of cleanliness of the surfaces.

29. Ling, F. F. and E. Saibel
On kinetic friction between unlubricated metallic surfaces. WEAR 1:167 –172, 1957.

A theory of friction between unlubricated metallic surfaces in sliding contact is proposed. For sliding conditions in which hot or cold welding of asperities is possible, the current weld-junction theory leads to a simple formulation of the friction coefficient under ideal conditions. This result differs from Bowden and Tabor's in that the coefficient of friction is found as the ratio of shear strength to yield pressure multiplied by a factor in which additional effects of load, relative velocity, temperature, and other physical properties appear. In arriving at this factor, the process of welding and fracturing of surface asperities is postulated to be a unimolecular reaction.

30. Owens, G.E., Comp.
ELECTRICAL CONTACTS IN SPACE ENVIRONMENT: AN ANNOTATED BIBLIOGRAPHY. Lockheed Missiles and Space Div., Sunnyvale, Calif. Special Bibliography no. SB-61-23, May 1961. 84p.

Includes references on friction in a high vacuum.

31. Riehl, W. A., W. C. Looney and S. V. Caruso
COMPATIBILITY OF ENGINEERING MATERIALS WITH SPACE ENVIRONMENT. Army Ballistic Missile Agency, Huntsville, Ala. Final Report, Part II, ABMA (6), 25 Oct 1960. 60p.

Compatibility of materials with vacuum are investigated.

32. Space vacuum still poses problems.
MACHINE DESIGN 33(20):12, 28 Sep 1961.

Brief report of work at Hughes Aircraft. Cold welding occurs in a few days in space conditions because of molecular attraction and the lack of surface films.

33. Spalvins, T. and D. V. Keller
ADHESION BETWEEN ATOMICALLY CLEAN METALLIC SURFACES. PART I, BULK ADHESION.
Syracuse University Research Institute, N.Y.
Report no. S.U.R.I. MET. E. 905-621SA,
1 Feb 1962. p.1–12. NASA N62-13821 (Presented at the American Vacuum Society, Metallurgy Division Conference, New York U., June 18, 19, 1962)
NASA N62-15678.

Microwelding in an ultrahigh or high vacuum was investigated. Two clean metallic surfaces were brought into touch contact at a near-zero force. Complete adhesion occurred between couples of Fe-Al, Ag-Cu, Ni-Cu, and Ni-Mo. No adhesion occurred between Cu-Mo, Ag-Mo, Ag-Fe, Ag-Ni or Ge-Ge. Results suggest that adhesion depends on the physical chemistry of the surfaces rather than the mechanical aspects of the contact area.

34. Steele, O. P. III
Electric equipment checked for space environment.
SPACE/AERONAUTICS. 36(3):75–79, Sep 1961.

A series of tests has been conducted to find bearing materials and an electrical insulation system capable of withstanding high temperatures under vacuum conditions. Twenty combinations of bearing materials were tested for both static and dynamic friction under vacuum at temperature levels of up to 1000°F.

35. Super vacuum causes metal evaporation, cold welding. WELDING ENGINEER. 46:41, Nov 1961.

36. Vacuum in space causes cold welding
WELDING DESIGN & FABRICATION. 35:46, Jan 1962.

Vacuum testing of cold rolled steel specimens was performed to determine surface evaporation and atom bonding characteristics of metal in outer space. The use of low pressure greases, molybdenum disulfide and Teflon bearing material and pressures above 10^{-6} Torr and temperatures below 100°C were simulated to determine seizure and degassing prevention.

37. Vaidyanath, L. R. and D. R. Milner
Significance of surface preparation in cold-pressure welding. BRITISH WELDING JOURNAL 7(1):1–6, 1960.

Two-ply composites were roll-bonded and their weld strengths determined. Most work was performed on aluminum with a few check tests on copper. Several surface preparations were tried. Scratch-brushed surfaces had the best bond strength. Heating in air and cooling in a desiccator improved the weld strength, particularly of the poorer surfaces. Baking-out in a vacuum was very beneficial. The highest bond strengths were obtained when surfaces were scratch-brushed immediately before roll bonding.

38. Vanderschmidt, G. F. and J. C. Simons, Jr.
Material sublimation and surface effects in high vacuum. In FIRST SYMPOSIUM ON SURFACE EFFECTS ON SPACECRAFT MATERIALS. F. J. Clauss, ed. N.Y. Wiley. 1960. p.247.

39. Von Vick, G.
Friction effects in a Satellite environment – the present state of the art. VACUUM 11(5–6):252–254, 1961.

A review of experiments and theories dealing with surface friction with the main emphasis on friction in a vacuum.

40. Von Vick, G.
LITERATURE RESEARCH PROGRAM ON HIGH VACUUM FRICTION. Lockheed Missiles and Space Div., Sunnyvale, Calif. (Van Nuys facility). Report no. LMSD/909963, 15 Jul 1959. 14p.

41. Wall, A. J. and D. R. Milner
Wetting and spreading phenomena in vacuum.
INSTITUTE OF METALS, JOURNAL 90(10):394–402,
Jun 1962.

The removal during vacuum brazing of oxide films on high temperature alloys containing aluminum was studied. The wetting of Cu-Al, Ni-Al and Fe-Al by various liquid metals in a vacuum is discussed. The mechanisms of penetration and spreading along the metal-oxide interface and their relationship to the brazing processes are also discussed.

42. Wallace, William B.
Vacuum studies give answer to materials for
space. PRODUCT ENGINEERING
33:74–75, 5 Feb 1962.

The effects of vacuum (as high as 10^{-12} Torr) on the vaporization of greases and other lubricants were studied. Seizure and cold welding of degassed steel are discussed.

43. Welding in a vacuum? MATERIALS IN
DESIGN ENGINEERING 55:12, May 1962.

Copper parts are cold welded in an ultra high vacuum. The adhesion and cohesion were studied, and the tensile strength and electrical properties were determined.

44. Willens, R. H.
Bearings for high vacuum applications.
REVIEW OF SCIENTIFIC INSTRUMENTS
31(5):574, May 1960.

SOURCE – AGENCY INDEX

SUBJECT INDEX